

SMD Technology Development Story for NASA Annual Technology report

The role of the Science Mission Directorate (SMD) is to enable NASA to achieve its science goals in the context of the Nation's science agenda. SMD's strategic decisions regarding future missions and scientific pursuits are guided by Agency goals, input from the science community—including the recommendations set forth in the National Research Council (NRC) decadal surveys—and a commitment to preserve a balanced program across the major science disciplines. Toward this end, each of the four SMD science divisions—Heliophysics, Earth Science, Planetary Science, and Astrophysics—develops fundamental science questions upon which to base future research and mission programs. Often the breakthrough science required to answer these questions requires significant technological innovation—e.g., instruments or platforms with capabilities beyond the current state of the art. SMD's targeted technology investments fill technology gaps, enabling NASA to build the challenging and complex missions that accomplish groundbreaking science.

SMD works to ensure that NASA actively identifies and invests in the right technologies at the right time to enable the Agency's science program. SMD technology development is part of a comprehensive Agency-wide strategy that involves coordination with the NASA Chief Technologist and other Agency mission directorates. This coordination helps ensure that crosscutting technology development needs are identified across the Agency and that there is optimal return on investments to fulfill those needs. SMD accomplishes technology development through technology programs established in each of its four science divisions. If a technology development effort reaches a NASA Technology Readiness Level (TRL) that is high enough, an SMD flight program may use it for a specific mission application. In FY16, SMD supported approximately 250 technology development efforts. While only some of these endeavors can be highlighted in this report, each of the SMD science divisions significantly advanced technologies in FY16 to enable NASA's science agenda.

Several technology developments funded by the Planetary Science Division (PSD) achieved milestones this year that will enable future planetary and deep space missions. PSD-sponsored thermoelectric research resulted in demonstration of advanced Radioisotope Thermoelectric Generators that are twice as efficient as heritage devices. An innovative three-dimensional weaving technique is being used to develop a lightweight, yet robust, heat shield to protect future spacecraft against the extreme heat encountered upon entry into planetary atmospheres. Two newly designed neutron spectrometers will fly onboard LunaH-Map—a CubeSat scheduled for launch in 2018 on the first integrated flight of NASA's Space Launch System (SLS) and Orion spacecraft. These efficient detectors will help map ice deposits near the lunar South Pole, which may enable future missions to the Moon.

SMD DIVISION FUNDAMENTAL SCIENCE QUESTIONS

HELIOPHYSICS

- What causes the Sun to vary?
- How do the geospace, planetary space environments and the heliosphere respond?
- What are the impacts on humanity?

EARTH SCIENCE

- How is the global Earth system changing?
- What causes these changes in the Earth system?
- How will the Earth system change in the future?
- How can Earth system science provide societal benefit?

PLANETARY SCIENCE

- How did our solar system form and evolve?
- Is there life beyond Earth?
- What are the hazards to life on Earth?

ASTROPHYSICS

- How does the universe work?
- How did we get here?
- Are we alone?

The Heliophysics Division is sponsoring several technology projects that will lead to greater understanding of the sun and its interaction with Earth. For example, a new carbon composite heat shield is under development to protect the upcoming Solar Probe Plus (SPP) mission when it travels closer to the sun than any mission has ever been before. In addition, a heliophysics mission—the CubeSat to study Solar Particles (CuSP)—was selected to launch on the first flight of NASA’s SLS in 2018. CuSP will orbit the sun in interplanetary space, carrying three instruments to measure incoming radiation that can create a wide variety of effects at Earth, from interfering with radio communications, to tripping up satellite electronics, to creating electric currents in power grids. CuSP will also test the possibility of creating a cost-effective network of space science stations out of a number of similar small satellites.

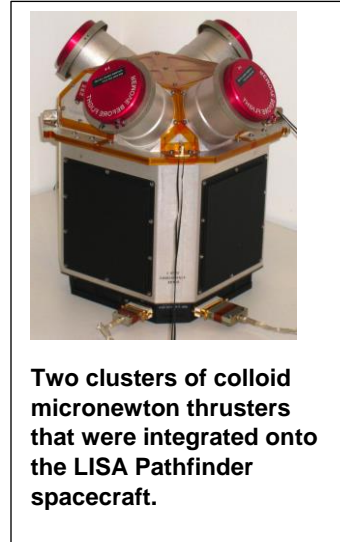
Technology developments funded by the Earth Science Division (ESD) are currently enabling capabilities that are helping scientists to understand our home planet. The Ozone Differential Absorption Lidar (DIAL) instrument is a compact airborne lidar that measures high accuracy profiles of ozone while also providing aerosols and cloud data. This instrument was deployed in August 2016 to support a five-year investigation to study the climate impacts of African biomass burning. ESD is also making strides to develop new instruments for potential use on upcoming space missions. A groundbreaking Carbon Dioxide (CO₂) Sounder Lidar instrument employs a new type of laser system that will enable collection of global carbon dioxide measurements around the clock—a capability that is not possible with existing space instruments.

Several technologies developed by the Astrophysics Division made important contributions to advance scientific capabilities. A new type of thruster system designed to control a spacecraft’s position to within a millionth of a millimeter was successfully deployed onboard the LISA Pathfinder mission. NASA’s Balloon Program Office completed the second test flight of its Super Pressure Balloon (SPB) in July, setting a new duration record for a mid-latitude flight of a large scientific research balloon. An instrument that employs newly developed absorber technology—the High-Resolution Airborne Wideband Camera-plus (HAWC+)—was installed on NASA’s Stratospheric Observatory for Infrared Astronomy (SOFIA). In conjunction with STMD, SMD also sponsors development of the Wide-Field Infrared Survey Telescope (WFIRST) Coronagraph, the first high-contrast stellar coronagraph to be used in space. The WFIRST Coronagraph development effort progressed significantly in FY16, passing a key review and decision milestone.

New Micronewton Thruster Technology Successfully Used in Space

Infusion

On December 3, 2015, the LISA Pathfinder mission blasted into space carrying the most stable spacecraft thruster system ever qualified for use in space. Developed by NASA JPL, the Space Technology 7 (ST-7) Disturbance Reduction System (DRS) is designed to control the spacecraft's position to within a millionth of a millimeter. ST-7 DRS consists of clusters of colloid micronewton thrusters and control software residing on a dedicated computer. To operate, the thrusters apply an electric charge to small droplets of liquid and accelerate them through an electric field. As of January 10, 2016 all eight identical thrusters passed their functional tests onboard the spacecraft, marking the first time this new thruster technology was used in space. ST-7 DRS is one of two thruster systems being tested on the LISA Pathfinder mission (the other system was developed by the European Space Agency). Six weeks after launch, the spacecraft reached its orbit around "L1," a virtual point in space some 1.5 million km from Earth towards the sun. The LISA Pathfinder science mission began on March 1, 2016, and operations will extend for at least six months. During the first phase of the mission's science operations, the thruster technology system designed by the European Space Agency was used. The ST-7 DRS formally began nominal operations on August 14, 2016, and will operate for 90 days.



Benefit

ST-7 DRS delivers extremely small pulses of energy (5 to 30 micronewtons of thrust) to precisely control the LISA Pathfinder spacecraft. Precise spacecraft control is vital to achieve the LISA Pathfinder goal: demonstrating technology concepts required to detect low-frequency gravitational waves. Gravitational waves are incredibly faint. The magnitude of oscillation is on the order of tens of picometers—one picometer is one trillionth of a meter—which is why it is critical to keep the spacecraft stable enough to detect the waves.

The LISA Pathfinder contains two test masses—objects designed to respond only to gravity (to the greatest extent possible). These test masses are made of a mixture of gold and platinum so that they will be very dense, but also non-magnetic. They each weigh about four pounds (two kilograms) and measure 4.6 centimeters on each side. The LISA Pathfinder spacecraft is intended to shield the test masses from external forces so that they follow a trajectory determined only by the local gravitational field. The dominant force to overcome is solar pressure, which pushes on the spacecraft and is the equivalent of about the weight of a grain of sand. By precisely measuring the position of the freely floating test masses, the ST-7 DRS uses its "micro-rocket" thrusters to keep the spacecraft centered about the test masses. In effect, the spacecraft essentially flies in formation with the test masses, using onboard sensor information (provided by the European LISA Technology Package) to control the thrusters and keep the

test masses totally isolated from external forces. By measuring their relative motion, a future mission could use such test masses as references in the quest to detect gravity waves.

There are numerous potential uses for the ST-7 DRS technology in the future, in addition to detection of gravity waves. For example, the system could be used to stabilize a future spacecraft that needs to be very still to detect exoplanets. ST-7 DRS could replace the reaction wheels that help control a spacecraft's orientation, reducing the overall mass of the spacecraft. The thruster system could also be used to enable spacecraft to fly in formation. For example, a constellation of small satellites flying together could use these thrusters to remain highly synchronized.

Development Team Leads

Phillip Barela of NASA JPL is the STS-DRS project manager.

John Ziemer of NASA JPL is the lead engineer for STS-DRS.

Charlie Dunn of NASA JPL is the STS-DRS Technologist.

Lead NASA Center: NASA JPL

Funding Organization: Science Mission Directorate's Astrophysics Division

Super Pressure Balloon Achieves Successful Flight

Infusion

After over 15 years of tests and development, NASA's Balloon Program team is on the cusp of expanding the envelope in high-altitude, heavy-lift ballooning with its super pressure balloon (SPB) technology. SMD technology investments that enabled the development of SPB—the first totally new balloon design in more than 60 years—include improved film and evolution of the balloon design and fabrication. The pumpkin-shaped, football stadium-size balloon is made from approximately 89,000 m² of polyethylene film—a material that is similar to a sandwich bag, but is stronger and more durable. The SPB is capable of ascending to a nearly constant density float altitude of about 33.5 km for flights lasting up to 100 days, given the right stratospheric conditions. Flying at mid-latitudes, the balloon is designed to endure the pressure changes that result from the heating and cooling of the day-night cycle. NASA expects the SPB to be capable of circumnavigating the globe once every one to five weeks, depending on wind speeds in the stratosphere. In May 2016, a 532,000-cubic-meter (18.8-million-cubic-foot) SPB launched from the Wanaka Airport in New Zealand, carrying the Compton Spectrometer and Imager (COSI)—a gamma ray telescope—as a mission of opportunity. The balloon completed a circumnavigation of the globe in under 15 days and set a new flight duration record for a mid-latitude flight of a large scientific research balloon with a flight time of 46 days, 20 hours, and 19 minutes.



The Super Pressure Balloon and COSI Instrument just prior to launch.

Benefit

NASA's scientific balloons offer low-cost, near-space access for scientific payloads in the ~450 kg weight class. Balloon campaigns are used to conduct scientific investigations in fields such as astrophysics, heliophysics, and atmospheric research. The long-duration flights enabled by SPB technology will allow extended observations of scientific phenomena, permit more sources to be surveyed, and provide more time to observe weak or subtle sources. In addition, such mid-latitude flights are

essential for making observations at night, a requirement for certain types of scientific investigations. These aspects greatly enhance the return on science, and combined with the relatively low cost of balloon missions, could permit the SPB to become a competitive platform for a number of scientific investigations that would otherwise need to launch into orbit.

Development Team Leads

Debbie Fairbrother from Wallops Flight Facility is the chief technologist for the SPB.

Rodger Farley (retired) from Goddard Space Flight Center was the balloon designer.

Henry M. Cathey, Jr. from New Mexico State University/Physical Science Laboratory was the Test Lead for the SPB Development.

Lead NASA Center: Goddard Space Flight Center's Wallops Flight Facility
Funding Organization: Science Mission Directorate, Astrophysics Division

WFIRST Coronagraph: Imaging Giant Exoplanets Around Nearby Stars

Description

The Wide-Field Infrared Survey Telescope (WFIRST) is the highest-ranked recommendation for a large space mission in the National Research Council (NRC) 2010 decadal survey, *New Worlds, New Horizons (NWNH) in Astronomy and Astrophysics*. The WFIRST coronagraph instrument (CGI) will be the first high-contrast stellar coronagraph in space. It will enable WFIRST to respond to the goals of NWNH by directly imaging and spectrally characterizing giant exoplanets similar to Neptune and Jupiter, and possibly even super-Earths (extrasolar planets with a mass higher than Earth's but lower than our Solar System's ice giants, Neptune and Uranus), around nearby stars. The WFIRST CGI includes both a Shaped Pupil Coronagraph (SPC) and a Hybrid Lyot Coronagraph (HLC).

Success Story

WFIRST successfully completed its Mission Concept Review (MCR) in December 2015, in preparation for its Phase-A start, and passed Key Decision Point A (KDP-A) in February 2016. In FY 2016, the coronagraph technology team continued to make progress, completing the integration of the Occulting Mask Coronagraph (OMC) testbed for a TRL-5 demonstration. In addition, Northrop Grumman Xinetics delivered all three testbed deformable mirrors (DMs).



The Occulting Mask Coronagraph testbed in a vacuum chamber.

Benefit

With achievement of these milestones, NASA is a major step closer to being confident that WFIRST will be able to directly image planets and dust disks around nearby stars. There are at least 15 radial-velocity exoplanets that both coronagraphs will be able to image in their dark hole regions in a few hours integration time each. The WFIRST coronagraph will enable scientists to see these exoplanets directly for the first time, and the images will be in their true colors (using some of the other color filters

in the CGI). The CGI is baselined as a technology demonstration instrument on WFIRST; it does not drive mission requirements beyond those needed for the Wide Field Instrument (WFI). However, with one year of allocated observing time out of a six-year mission, NASA expects that it will achieve breakthrough science, and will demonstrate key technology elements for follow-up missions, the next of which could be aimed at finding habitable Earth-like planets around nearby stars.

Development Team Lead

Feng Zhao at NASA JPL is the lead engineer for the CGI.

Lead NASA Center: NASA Jet Propulsion Laboratory

Funding Organization: Science Mission Directorate and Space Technology Mission Directorate

For more information: <http://techport.nasa.gov/view/17551>

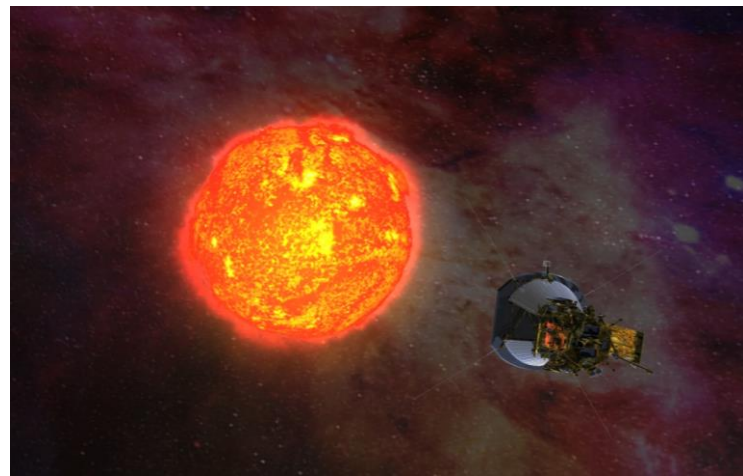
New Heat Shield to Protect Mission to the Sun

Infusion

NASA-sponsored technology has been employed to develop a state-of-the-art heat shield that will enable an important Heliophysics mission—the Solar Probe Plus (SPP). The newly developed carbon composite heat shield will protect the spacecraft from the extreme temperatures it will experience as it travels closer to the sun than any spacecraft has ever been before. The 8-foot diameter, 4.5-inch-thick, carbon-foam-filled solar shield will be placed atop the spacecraft body, facing the sun.

Benefit

This new heat shield will enable SPP to meet its goal of answering two fundamental science questions: (1) Why is the sun's outer atmosphere so much hotter than the sun's visible surface? and (2) What accelerates the solar wind that affects Earth and our solar system? To gather the data needed to understand these phenomena, SPP will fly into the sun's outer atmosphere—the corona—to make in situ measurements of the solar wind. The solar wind is a supersonic stream of mostly charged particles continuously emitted by the sun into the interplanetary medium. Disturbances in the solar wind can generate disruptions in near-Earth space—such as geomagnetic storms—that interfere with radio communications and GPS applications. To gather its data, SPP will orbit the sun 24 times, using seven different Venus fly-bys to gradually reduce its distance from the sun. During its closest three passes, SPP will be just 3.8 million miles from the surface of the sun—about seven times closer than any previous spacecraft. Although SPP will be exposed to temperatures up to 2,500° Fahrenheit (about 1,400° Celsius), the newly developed heat shield will help maintain a payload temperature close to room temperature, which will enable the suite of instruments on the spacecraft to function. Manufacture of the qualification model of the SPP heat shield will be completed in the fall of 2016. Although the Thermal Protection System (TPS) has already been qualified, the full



Artist's rendering of Solar Probe Plus, solar panels folded into the shadows of its protective heat shield, as it gathers data on its approach to the Sun. (Credit: NASA/JHU APL)

scale qualification model will serve to prove that the manufacturing process is repeatable on a large scale.

Development Team Leads

Elizabeth Congdon, Theodore Hartka, and Douglas Mehoke from the Johns Hopkins University/Applied Physics Laboratory were the lead developers.

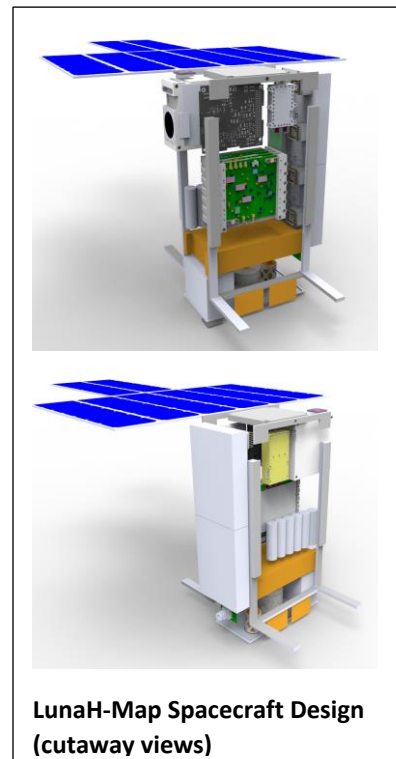
Lead NASA Center: Goddard Space Flight Center

Funding Organization: Science Mission Directorate

LunaH-Map Incorporates Newly Developed Spectrometers to Map Hydrogen on the Moon

Description

The Lunar polar Hydrogen Mapper (LunaH-Map) mission is one of 13 CubeSats scheduled for launch on the first integrated flight of NASA's Space Launch System (SLS) and Orion spacecraft in 2018. LunaH-Map will carry two newly designed neutron spectrometers (Mini-NS) to produce high-resolution maps of near-surface hydrogen. The presence of hydrogen indicates the presence of water, and LunaH-Map will provide important constraints on the location and abundance of ice deposits near the lunar South Pole. The spectrometers on LunaH-Map will measure the energies of neutrons that have interacted with and subsequently leaked back out of the material in the top meter of the lunar surface. To accomplish this task, the mission will employ new technology—an elpasolite scintillation detector—in an array of neutron detectors mounted to one face of the spacecraft. These new detectors enable efficient neutron detection capability in a small package, making them ideal for use on a CubeSat platform.



LunaH-Map Spacecraft Design
(cutaway views)

Success Story

The LunaH-Map team has completed or is working toward the following milestones in 2016:

- Passed a Mission-Level Initial Accommodation Audit in February
- Completed preliminary vibration test on Mini-NS modules in May and August
- Completed Mini-NS Preliminary Design Review in June
- Completed and passed Spacecraft Preliminary Design Review in July
- Scheduled Mini-NS Engineering Development Unit delivery to Arizona State University in

September

Benefit

LunaH-Map will produce maps of hydrogen abundance with relatively high spatial resolution for a neutron detector from orbit, and will demonstrate the capability of a CubeSat platform to acquire neutron counts from planetary surfaces. Understanding the distribution of hydrogen within

Lead NASA Center: NASA Headquarters

Funding Organization: Science Mission Directorate

permanently shadowed regions of the Moon will help planetary scientists understand the origin of polar volatiles and will help NASA plan future missions to the Moon. Knowing the location and volume of ice deposits will also be vital to future Moon missions that plan to make use of in situ resources—for example, a human mission to the Moon. LunaH-Map will also use a highly efficient ion propulsion system to maneuver itself from the SLS into a stable lunar orbit, and finally a science mapping orbit.

Development Team Leads

Craig Hardgrove at Arizona State University is the lead developer for the LunaH-Map system.

Segmented Modular Thermoelectric Technology for More Capable Power Sources

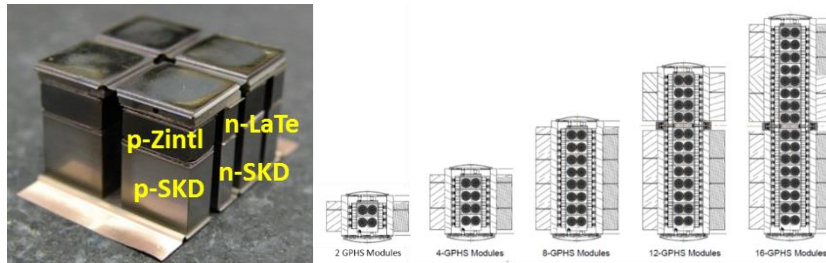
Description

The NRC's 2011 decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, articulates the continuing need for NASA planetary science missions to achieve scientific goals. Radioisotope Thermoelectric Generators (RTGs) have consistently demonstrated their extraordinary reliability and longevity for deep space and planetary missions, producing electricity and heat for decades under the harsh conditions of deep space without refueling. More efficient high-temperature materials and robust modular device configurations would provide: (1) full use of the exergy available from high-grade heat sources, (2) higher power output for a given heat source, (3) lower-mass power systems, and (4) scalability to higher-power space and terrestrial applications (from 100 W-class to multi-kW systems).

Success Story

NASA's steady investment in thermoelectric research and development has led to the identification of higher performance materials and the successful demonstration of segmented modular devices with twice the conversion efficiency of heritage technologies. For example, newly developed segmented modular devices operate at 15% conversion efficiency, versus 7.5% for heritage Si-Ge (silicon-germanium) General Purpose Heat Source (GPHS) RTG

devices and 7.1% for heritage PbTe/TAGS (lead-telluride/tellurium-antimony-germanium-silver) Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) devices. The new technology builds upon skutterudite (SKD) materials currently being matured by industry for potential infusion into an Enhanced MMRTG. In 2016, the team solved materials and device engineering challenges related to the stability of the hot-side thermoelectric/metal interconnect interface and packaging with ultra-low thermal conductivity, supercritically dried, opacified aerogel. These solutions enabled initiation-of-life performance testing of this modular technology in relevant environments.



Left: High Temperature Segmented Thermoelectric Module Technology with 2X efficiency gain over heritage radioisotope power system technology. Right: Modular System Concept derived from the GPHS-RTG Flight System and the previous modular RTG Ground Demonstration System.

Benefit

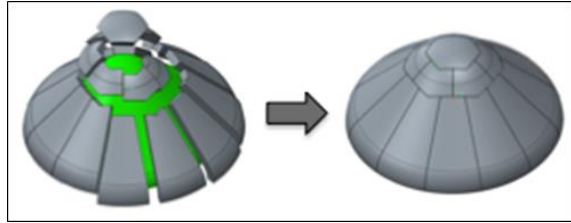
The high temperature Segmented Thermoelectric Module technology makes more efficient use of high-grade GPHS, and could enable more capable, high-specific-power, modular RTG concepts. This approach would allow mission planners maximum flexibility with power system sizing, minimizing the number of units for any given mission, thus simplifying spacecraft accommodation and potentially reducing Plutonium-238 fuel and system production costs. This technology has also attracted interest for application to various waste-heat recovery and energy efficiency terrestrial fields, including the oil and gas industry, solar thermal plants, and mobile defense platforms.

Lead NASA Center: NASA Jet Propulsion Laboratory
Funding Organization: Science Mission Directorate
For more information: <http://techport.nasa.gov/view/10857>

Specialized Weaving Techniques Enable Improved Heat Shield Capabilities

Description

The NRC Planetary Science Decadal Survey has recommended that NASA consider in situ science missions to Venus and Saturn as a high priority in the New Frontiers competed mission set. To reach the surface of these planets, missions will require heat shields that are capable of withstanding very extreme entry environments, but are not as heavy as heritage carbon phenolic heat shields. To respond to this need, NASA and its industry partners are developing an innovative way to design and manufacture a family of ablative thermal protection system (TPS) materials using commercially available weaving technology. This new approach—called Heat shield for Extreme Entry Environment Technology (HEEET)—leverages the way three-dimensional (3-D) weaving is used to manufacture aircraft parts made of carbon composite materials. To manufacture TPS materials with the desired properties, fibers of different compositions and variable yarn densities are accurately placed in a 3-D structure. Three-dimensional weaving extends the traditional two-dimensional (2-D) weaving by interconnecting woven material in the third direction, enabling the manufacturing of materials that are more robust to the entry environment. The panels are then infused with resins and cured to lock the fibers in place. Using advanced modeling, design, and manufacturing tools to optimize the weave for overall improved performance, the HEEET project has manufactured a new family of TPS materials and tested them for a wide variety of entry conditions.



A drawing of the individual components that make up a heat shield (left) and the fully assembled heat shield with integrated seams bonded to the structure underneath (right).

Success Story

In November 2015, the HEEET team successfully tested the seam concept at extreme conditions (heat fluxes of $\sim 6500 \text{ W/cm}^2$ and 5 atm. Pressure). In December 2015, the HEEET team designed an innovative way to test seams under elevated temperatures and conducted preliminary seam structural testing. In June 2016, Applied Aerospace Structures Corp. completed the fabrication of two composite carrier structures as per HEEET team design. Infusion of large-scale woven preforms and molding and machining has been successfully demonstrated by Fiber Machines Inc. (FMI), NASA's industrial partner/vendor. Technology transfer to FMI will enable future New Frontier mission proposers to baseline HEEET with confidence. At the New Technology Day in June 2016, SMD and STMD jointly identified HEEET as a new NASA technology for infusion into the upcoming New Frontiers opportunities.

Benefit

Depending on the mission design, peak heat-flux during entry can reach about 10,000 W/cm² for both Venus and Saturn, and the peak pressure can range up to about 1,000 kPa. HEET is designed to withstand these conditions and at the same time provide mass efficiency far superior to that of the heritage carbon phenolic material used for legacy missions. In addition to providing thermal protection, the 3-D weave also increases the mechanical robustness of the TPS material.

Development Team Leads

Dr. Don Ellerby at NASA Ames Research Center is the HEET Technical Lead

Dr. Ethiraj Venkatapathy at NASA Ames Research Center is the HEET Project Manager

Lead NASA Center: Ames Research Center

Funding Organization: Space Technology Mission Directorate

For More Information: <https://techport.nasa.gov/view/13634>